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Reviewing the potential and cost-effectiveness of grid-connected solar PV in Indonesia on a provincial level

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ABSTRACT

Photovoltaic (PV) energy could play a large role in increasing the electrification ratio and decreasing greenhouse gas emissions in Indonesia, especially since Indonesia comprises over 17,000 islands which is a challenge for the distribution of fuels and modern grid connection. The potential of grid-connected PV depends on, a.o. population, electrification ratio, irradiance, electricity demand, electricity generation costs and the urbanization ratio. Large spatial differences exist for these factors in Indonesia, therefore this study aims to assess the energetic potential and cost-effectiveness of grid-connected PV in Indonesia on a provincial level. Taking restrictions of the electricity demand during day-time and a minimal base load of conventional power systems into account, the total potential of grid-connected PV systems is about 27 GWp, generating 37 TWh/year, which is about 26% of the total electricity consumption in Indonesia over 2010. In the eastern provinces of Indonesia the LCOE of PV in grid-connected urban areas is lower than the cost of present electricity generation and could be a viable alternative if excluding high subsidies for electricity production.

Contents

1. Introduction

The Indonesian government is facing enormous challenges to improve the Indonesian electricity system in order to reach their future goals on grid penetration and GHG emission reduction [1,2]. In the period from 1987 to 2009 electricity production boosted by 620% [3] and it is expected that the future electricity demand continues to increase steadily by 9% annually [2]. Although Indonesia has abundant renewable energy resources (Table 1), its electricity production was still highly relying on coal (35%) and oil (26%) in 2010 [4], resulting in a high CO_2 intense electricity generation [5]. At current production rates the national gas and

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oil reserves will be depleted in the coming decades [6,7], therefore the share of coal is expected to increase in the near future due to its relatively low cost, availability and domestic industry.

The electricity price in Indonesia is heavily subsidized, for instance the government allocated an amount of 5.1 billion US dollar for electricity subsidies for the year 2012 [8] leading to a reduction of consumer price of electricity, which is significant lower compared with other Southeast Asian countries [5]. Especially on remote islands outside the main islands Java and Bali expensive diesel is used to generate electricity in a relatively inefficient way [2], which adds to the subsidy burden of the government, taking badly needed resources away from improving infrastructure [9]. For instance at the province East Nusa Tenggara the actual electricity production costs are about 15 $ct/kWh whereas the average price sold is less than 8 $ct/kWh [10]. The amount of subsidies for electricity and the dependency on fossil fuels and its inherent distribution problems will have an adverse effect on the Indonesian economy, therefore the government should take action toward using more renewable energy resources [5,11,12].

According to PLN [4] the total electricity production was 164 TWh in 2010 of which 12% comes from renewables, mainly hydro and geothermal. The share of solar energy is negligible and so far focus was mainly on standalone small scale PV systems like solar home systems and village systems [13], with modest success [14].

Since Indonesia comprises over 17,000 islands the distribution of fuels and energy is a challenge due to this geographically dispersed situation, by differences in developments between the main islands Java/Bali and the others as well as between urbanized and rural regions. This is one of the reasons that the average electrification ratio of households in Indonesia, which was 66% in 2010 [4], is one of the lowest compared with neighboring countries [2,5]. As can be seen in Fig. 1, large differences exist among provinces. For instance, high electrification ratios of more than 90% can be found in the provinces Jakarta and Aceh, while low electrification ratios of 24% can be found in Papua and East Nusa Tenggara. Besides, the inequity between urban (94%) and rural (32%) electrification is the largest in Indonesia compared with other big developing countries [5,16]. This is related to the poverty distribution in Indonesia [17], regions with high poverty ratios are less attractive for investors, because in general the

Table 1
Renewable energy potentials in Indonesia [7,15], ratio of installed capacity vs. resource potential.

Energy source	Resources	Installed capacity (GW)	Ratio (%)
Hydro	75.7 GW	4.2	6
Geothermal	27.0 GW	1.2	4
Mini/micro-hydro	0.5 GW	0.2	46
Biomass	49.8 GW	0.3	1
Solar	4.8 kWh/m^2/day	0.01	–
Wind	9.3 GW	0.0006	0

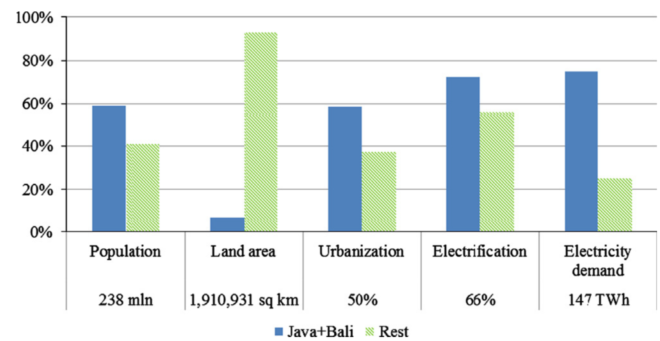

Fig. 2. Comparison of the population, land area, urbanization ratio, electrification ratio and electricity demand for the islands Java–Bali with the rest of Indonesia. Below the bars total figures are shown for each category.

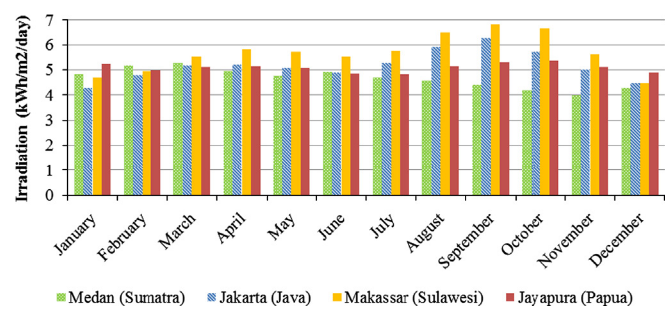

Fig. 3. Daily average solar irradiation (kWh/m^2/day) for four Indonesian cities for each month over a period of 22 years between 1983 and 2005 [22].

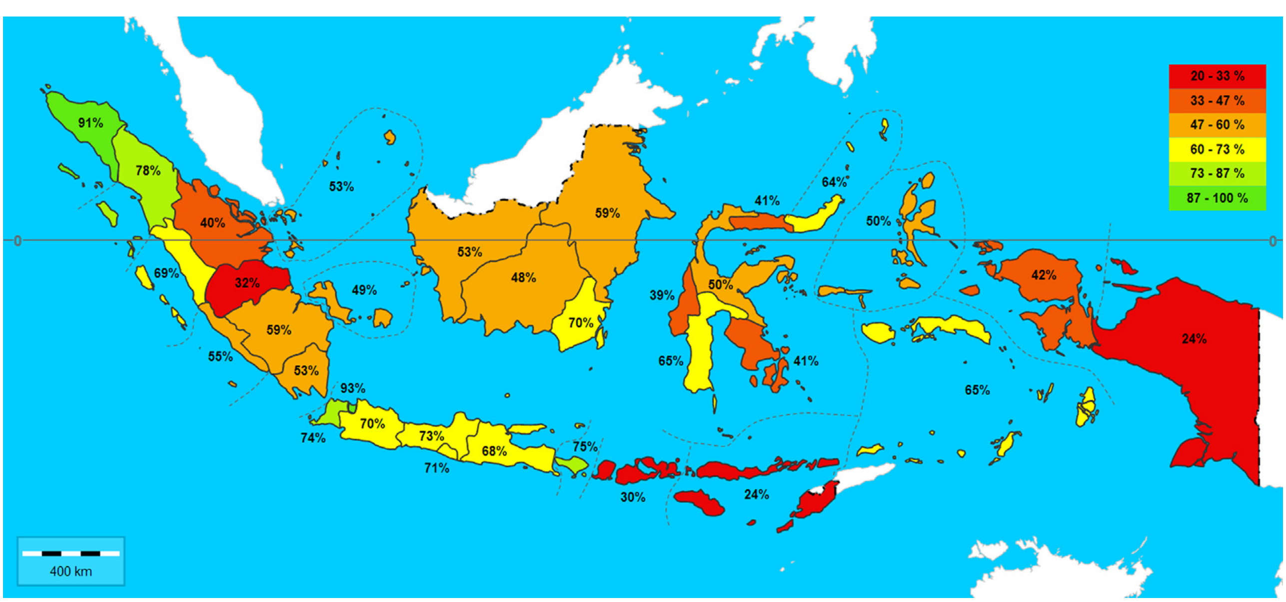

Fig. 1. Electrification ratio of households per province in Indonesia in 2010 [4].

Fig. 4. The population density per province of Indonesia.

profits are low and the financial risks are high. To improve this situation the government aims to increase the electrification ratio to 90% by 2019 [2].

Electricity is transmitted through seven integrated networks, which includes Java–Bali–Madura and Sumatra grids, and roughly 600 isolated networks spread over the rest of the islands [18]. This is related to the population density in these areas, which allow investments in grid extensions. About 60% of the 238 million Indonesians live on the islands Java and Bali [19], in general these islands are better developed than the rest of Indonesia, see Fig. 2. Logically, many of Indonesia's small and isolated islands are hardly reachable by a centralized power grid [20].

In this paper we will evaluate how photovoltaic (PV) energy can play a role in increasing the electrification ratio in Indonesia and decreasing the GHG emissions at the same time. To start with we would get better insight in the solar radiation distribution in Indonesia. It can be divided into two regions, one with approximately 4.5 kWh/m^2/day with a monthly deviation around 10% for Western regions and for the Eastern regions this amount is about 5.1 kWh/m^2/day with a monthly deviation around 9% [21]. In many energy potential studies about Indonesia [5], the total resource potential of solar PV is often described as 4.8 kWh/m^2/day, which is the average solar irradiation in Indonesia. In Fig. 3 the daily average solar irradiation (kWh/m^2/day) for four Indonesian cities for each month is presented. It indicates that the variability in practice can be between 4 up to 6.9 kWh/m^2/day.

A study about the actual potential of PV systems in GW is lacking so far, making comparisons among resources difficult. In theory, the energy potential is equal to the country's area times the average irradiation and the average system efficiency, however this is not very realistic; the actual potential depends on various factors, a.o. the irradiation, land availability, electricity demand and the cost of electricity [23].

Large spatial differences exist for these factors in Indonesia, therefore this study aims to assess the potential and cost-effectiveness of grid-connected PV in Indonesia on a provincial level. To assess the actual potential of grid-connected PV, we developed a mathematical model which is based on literature studies and available data for each of the 33 provinces (see Fig. 4) in Indonesia, a.o. population, electrification ratio, irradiance, electricity demand, electricity generation costs and the urbanization ratio.

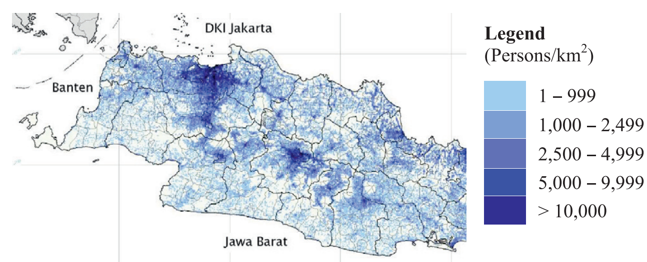

Fig. 5. Population density map of the western part of Java. The map is compiled from results from the 2000 Population Census by BPS Indonesia and Japan International Cooperation Agency [25].

Since data about geographic locations with grid connection are not publicly available, a new method has been developed to determine the area suitable for grid-connected PV based on available data of land area, population, electrification ratio and urbanization ratio per province.

Based on availability of data this study focuses on 2010. A preliminary version of the method has been documented in Ref. [24]. Here we present the full procedure inclusive of a sensitivity analysis.

In Section (2) the methodology, the applied input data and the constraints of this model will be described. Section 3 presents the results for energy potential and cost-effectiveness along with a sensitivity analysis, followed by a discussion and conclusions in Section 4.

2. Research methodology

To calculate the actual potential of grid-connected PV the following general assumptions have been made: (1) population density is a major factor, (2) other renewable energy technologies are not taken into account, (3) the calculations will be based on grid-connected systems without storage, (4) the model is based on a provincial level, so local variations inside the province itself are outside the scope of this study. Furthermore we describe below how we determined suitable area (2.1) and energy demand (2.2).

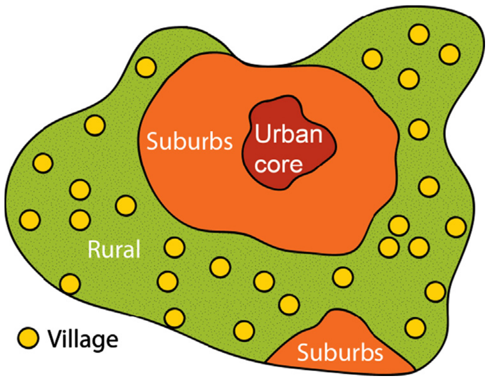

Fig. 6. Schematic representation of the classification of the various areas inside a province (1) urban core (red), (2) suburbs (orange), (3) villages (yellow) and (4) rural areas (green) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

2.1. Suitable area

Since this study focuses on grid-connected PV, the suitable area for PV is limited to areas where an electricity grid is already available. This area with grid connection is hard to determine due to a lack of data about grid distribution at the low voltage level. In general only the major high voltage transmission lines are known, therefore a new method is developed to determine this area. A relation among the population, population density, urbanization ratio and the electrification ratio of the particular province is proposed. As can be seen in Fig. 5 the population is not uniformly distributed over the available land area.

Since an electricity grid is expensive and only cost-effective in densely populated areas, we expect that densely populated areas have priority over sparsely populated areas regarding grid connection [5]. In this study each province is divided into four different areas based on the population density. In order from high to low population densities, these areas are: (1) urban cores, (2) suburbs, (3) villages and (4) rural areas, see Fig. 6. It is assumed that the electricity grid is extended in the same sequence, from urban cores to rural areas. Furthermore, it is assumed that rural areas do not have an electricity grid and are not suitable for grid-connected PV.

The population N in province p that is connected to the grid, $N_{p,grid}$, is determined as follows:

$$N_{p,grid} = N_p \times ER_p \tag{1}$$

where N_p is the population of the province [19] and ER_p is the electrification ratio of the households in the province [4].

The population in the urban core with grid connection in province p, $N_{p,grid,1}$, is determined as follows:

$$N_{p,grid,1} = \begin{cases} N_{p,1}, & N_{p,1} \leq N_{p,grid} \\ N_{p,grid}, & N_{p,1} > N_{p,grid} \end{cases} \tag{2}$$

where $N_{p,1}$ is the population living in the urban core (kota) according to BPS [5]. The total population in the suburbs and urban cores of a province, $N_{p,1,2}$, is determined as follows:

$$N_{p,1,2} = N_p \times UR_p \tag{3}$$

where UR_p is the urbanization ratio of the province according to Bureau of Statistics (BPS) [19]. BPS classifies a village as urban if it satisfies the following three conditions: (a) a population density of at least 5,000 persons/km^2, (b) 25% or less of the households working in the agriculture sector, and (c) eight or more urban-related facilities like post office, bank, cinema, hospital, and school [26].

Table 2
Assumptions for some parameters for the calculation of the potential of grid-connected PV.

Variable	Value	Unit
$\overline{ND_1}$	8000	Persons/km^2
$\overline{ND_2}$	5000	Persons/km^2
$\overline{ND_3}$	1000	Persons/km^2
LA_1	5	%
LA_2	10	%
LA_3	15	%
PR_1	75	%
PR_2	80	%
PR_3	70	%

Next, the suburban population connected to the grid, $N_{p,grid,2}$, is determined according to

$$N_{p,grid,2} = \begin{cases} N_{p,1,2} - N_{p,grid,1}, & N_{p,1,2} \leq N_{p,grid} \\ N_{p,grid} - N_{p,grid,1}, & N_{p,1,2} > N_{p,grid} \end{cases} \tag{4}$$

Similarly, the population in villages with grid-connection, $N_{p,grid,3}$, is determined:

$$N_{p,grid,3} = \begin{cases} N_{p,grid} - N_{p,1,2}, & N_{p,1,2} < N_{p,grid} \\ 0, & N_{p,1,2} \geq N_{p,grid} \end{cases} \tag{5}$$

Now the populations for various areas are determined, the corresponding land areas can be calculated. The sizes of the various areas are obtained by dividing the population of the distinguished area by its average population density. For simplicity, the average population density in Indonesia for these distinguished areas is equal for each province, see Table 2.

The land area of the urban core with grid-connection is calculated as follows:

$$A_{p,grid,1} = \begin{cases} \frac{N_{p,grid,1}}{\overline{ND_1}}, & \frac{N_{p,grid,1}}{\overline{ND_1}} \leq A_{p,0.8} \\ A_{p,0.8}, & \frac{N_{p,grid,1}}{\overline{ND_1}} > A_{p,0.8} \end{cases} \tag{6}$$

where $A_{p,grid,1}$ is the provincial urban core area in km^2 wherein the population is connected to the electricity grid, $\overline{ND_1}$ is the average population density of urban cores in Indonesia in persons/km^2 and $Ap_{0.8}$ is 80% of the total land area of the province in km^2 [27]. It is assumed that at least 20% of the land area of each province is not populated, which affects the island Java only, because of the high population density. For the Special Capital Region of Jakarta an exception has been made and 100% of the total land area can be populated, since it is a relatively small area (664 km^2) and very densely populated.

The suburban area is determined in a similar way:

$$A_{p,grid,2} = \begin{cases} \frac{N_{p,grid,2}}{\overline{ND_2}}, & \frac{N_{p,grid,2}}{\overline{ND_2}} \leq A_{p,0.8} \\ A_{p,0.8} - A_{p,grid,1}, & \frac{N_{p,grid,2}}{\overline{ND_2}} > A_{p,0.8} \end{cases} \tag{7}$$

The area of the grid-connected villages can be found using the following formula:

$$A_{p,grid,3} = \begin{cases} \frac{N_{p,grid,3}}{\overline{ND_3}}, & \frac{N_{p,grid,3}}{\overline{ND_3}} \leq A_{p,0.8} \\ A_{p,0.8} - (A_{p,grid,1} + A_{p,grid,2}), & \frac{N_{p,grid,3}}{\overline{ND_3}} > A_{p,0.8} \end{cases} \tag{8}$$

where $A_{p,grid,3}$ is the area in km^2 of the villages in the province wherein the population is connected to the electricity grid and $\overline{ND_3}$ is the average population density of villages in Indonesia.

Although it is theoretically possible that the areas $A_{p,grid,2}$ and $A_{p,grid,3}$ are equal to zero based on Eqs. (6)–(8), this only happens

Table 3
Assumptions of the electricity demand during daylight time for each customer type of PLN [4].

Customer type	Demand daylight time (%)
Residential	40
Industrial	80
Business	60
Social	70
Governmental building	90
Street lighting	0

Table 4
Input data per province.

Province	A[a] (×1000) (km^2)	N[b] (×mln)	UR[c] (%)	N_{city}[d] (×1000)	ER[e] (%)	H[f](kWh/m^2/day)
Banten	9.7	10.6	67	3878	74	4.8
West Java	35.4	43.1	66	9256	70	4.8
East Java	47.8	37.5	48	4832	68	4.9
Central Java	32.8	32.4	46	2823	73	5.5
Jakarta	0.7	9.6	100	9608	93	4.8
Yogyakarta	3.1	3.5	66	389	71	4.8
S. Kalimantan	38.7	3.6	42	805	70	4.8
E. Kalimantan	204.5	3.6	62	1531	59	4.8
W. Kalimantan	147.3	4.4	30	683	53	5.0
C. Kalimantan	153.6	2.2	33	201	48	4.8
Maluku	46.9	1.5	37	334	65	5.8
North Maluku	32.0	1.0	27	192	50	6.0
Bali	5.8	3.9	60	789	75	5.3
WNT	18.6	4.5	42	515	30	5.6
ENT	48.7	4.7	19	316	24	6.2
S. Sulawesi	46.7	8.0	37	1573	65	5.4
N. Sulawesi	13.9	2.3	45	681	64	5.9
Gorontalo	11.3	1.0	34	174	41	5.1
S.E. Sulawesi	38.1	2.2	27	371	41	4.9
C. Sulawesi	61.8	2.6	24	310	50	5.0
W. Sulawesi	16.8	1.2	23	-	39	5.5
W. Sumatra	42.0	4.8	39	1201	69	4.9
N. Sumatra	73.0	13.0	49	3124	78	4.5
S. Sumatra	91.6	7.5	36	1798	59	4.6
Lampung	34.6	7.6	26	1016	53	4.9
Jambi	50.1	3.1	31	569	32	4.6
Bangka-Belitung	16.4	1.2	49	163	49	4.5
Bengkulu	19.9	1.7	31	296	55	4.8
Riau	87.0	5.5	39	1056	40	4.4
Riau Islands	8.2	1.7	83	1095	53	5.1
Aceh	58.0	4.5	28	509	91	5.1
West Papua	97.0	0.8	30	118	42	5.1
Papua	319.0	2.8	26	234	24	5.0

[a] A is the area from Statistics Indonesia [27].
[b] N is the population from Statistics Indonesia [19].
[c] UR is the urbanization ratio from Statistics Indonesia [19].
[d] N_{city} is the total of the population living in city districts (kota) [19].
[e] UR is the urbanization ratio of the province [19].
[f] H is the average daily irradiation from NASA [22].

for the Jakarta province wherein the populations of the corresponding suburban and village areas are equal to zero.

The technical production potential of grid-connected PV systems for each province of Indonesia is calculated using the following formula:

$$E_{p,PV,pot} = d_y \eta H_p \sum_{i=1}^{3} LA_i A_{p,grid,i} PR_i \tag{9}$$

where $E_{PV,p,pot}$ is the potential annual electricity production of grid-connected PV of the province in GWh/year, d_y is the number of days per year, η is the efficiency of the PV modules, PR is the performance ratio, H_p is the average irradiation in kWh/m^2/day of the province, i is the area type (1=urban core, 2=suburban, 3=village) and LA is the land availability factor for grid-connected PV. In Table 2 the values for the various factors are presented.

The population density of 8000 persons/km^2 for urban cores is based on the average population density of the largest cities in Indonesia [28]. The population density of 5000 persons/km^2 for suburbs is the least to be classified as urban according to BPS [26]. The population density of 1000 persons/km^2 is assumed to be the average for rural villages with grid-connection in Indonesia.

In this study the selected PV technology is multi-crystalline silicon. The module efficiency (η) of multi-crystalline silicon is assumed to be 15%. The performance ratio (PR) of grid-connected PV in Indonesia is estimated to be 75% for urban cores and 80% for suburban areas. These values are slightly lower than European systems, because high ambient temperatures and high irradiance in this tropical climate will more prominently induce a temperature effect on the performance of crystalline silicon PV modules. Because of higher temperatures and shading due to surroundings, the PR for urban cores is assumed to be 5% lower compared with suburban areas. The PR of grid-connected PV is assumed to be 70% in rural areas, due to a lower and more unstable electricity demand and higher transmission losses due to longer distances.

2.2. Electricity demand

The amount of grid-connected PV in a particular province is related to the electricity demand of its population. The total amount of generated electricity by grid-connected PV (GWh) should not exceed the electricity demand in the province. The electricity demand is based on the data per province over 2010 from state electric company PLN [4]. It contains the total electricity consumption per customer type over the year 2010. Since no storage system is assumed, per customer type an assumption is made regarding the electricity demand during Indonesian daylight time, see Table 3. Further it is assumed that this demand profile is uniform in Indonesia.

An extra limitation of the total electricity generated by PV is related to the base load and the flexibility of the existing base load power plants. There is a minimum level to which conventional generators can be 'turned down' with minimal economic penalty [29]. The base load is assumed to be 80% of the electricity demand during night time and the minimal load constraint is assumed to be 90% of this amount.

$$E_{p,load,min} = E_{p,demand,night} \times 0.8 \times 0.9 \tag{10}$$

where $E_{p,load,min}$ is the minimal electricity produced by existing electric power systems and $E_{p,demand,night}$ is the electricity demand during night time of the province, both in GWh/year.

The maximum amount of electricity generated by PV $E_{p,PV,demand}$, based on the electricity demand is therefore

$$E_{p,PV,dem\ and} = E_{p,dem\ and,day} - E_{p,load,min} \tag{11}$$

where $E_{p,demand,day}$ is the electricity demand during daylight time of the province.

The yearly amount of electricity that can be supplied by grid-connected PV in a province, $E_{p,PV}$, is

$$E_{p,PV} = \min(E_{p,PV,demand}, E_{p,PV,pot}) \tag{12}$$

The produced electricity by PV per capita can be obtained by

$$E_{p,PV,capita} = \frac{E_{p,PV}}{N_{p,grid}} \tag{13}$$

Assuming identical electricity consumption per capita in each province, the electricity generated by PV per area type (e.g. urban)

can be determined by multiplying the $E_{p,PV,capita}$ by the population connected to the grid in this area.

$$E_{p,PV,i} = E_{p,PV,capita} \times N_{p,grid,i} \tag{14}$$

In Table 4 some of the input data per province is shown.

2.3. Costs

To be cost-effective, the levelized cost of energy (LCOE) of grid-connected PV must be lower or equal to the generation cost of electricity with existing technology. The LCOE is calculated according to the method from Campbell et al. [30]. To calculate the total cost of the PV system for each type of area i, first the annual capacity factor[1] , $CF_{p,i}$, is determined.

$$CF_{p,i} = \frac{d_y \times H_p \times \eta \times A_{p,grid,i} \times PR_i}{d_y \times h_d \times A_{p,grid,i} \times G_{STC} \times \eta} \tag{15}$$

where G_{STC} is the irradiance at Standard Test Conditions (STCs), which is 1000 W/m^2 and h_d is the number of hours per day. Eq. (15) can be simplified to

$$CF_{p,i} = H_p \frac{PR_i}{h_d} \tag{16}$$

Subsequently, the nominal PV system capacity, C, in watt-peak (Wp) per area type (urban, etc.) can be determined:

$$C_{p,i} = \frac{E_{p,PV,i} \times 10^9}{d_y \times h_d \times CF_i} \tag{17}$$

The initial investment, $I_{p,i}$, for each area type can be calculated as follows:

$$I_{p,i} = C_{p,i} \times P \tag{18}$$

where the installed system price (including BOS), P, is in \$/Wp.

$$RV_{p,i} = I_{p,i} \times RV \tag{19}$$

where $RV_{p,i}$ is the residual value of the PV system in province p and area type i after its lifetime and RV is a percentage of the initial investment representing its salvage value.

The annual operation costs AO in \$/kWp are determined as follows:

$$AO_{p,i} = C_{p,i} \times AO \tag{20}$$

The annual depreciation DP is calculated according to the straight line method:

$$DP_{p,i} = \frac{I_{p,i} - RV_{p,i}}{L} \tag{21}$$

where L is the lifetime of the PV system.

Next, the LCOE is calculated:where n is the year, TR is the tax rate, DR the discount rate and SDR the system degradation rate.

$$LCOE_{p,i} = \frac{I_{p,i} - \sum_{n=1}^{L}(DP_{p,i}/(1+DR)^n) \times (TR) + \sum_{n=1}^{N}(AO_{p,i}/(1+DR)^n) \times (1-TR) - (RV_{p,i}/(1+DR)^n)}{\sum_{n=1}^{N}(E_{p,PV,i} \times (1-SDR)^n/(1+DR)^n)} \tag{22}$$

The initial kWh is the energy production of the PV system in the first year and is equal to $10^3\ E_{p,PV}$.

In Table 5 the values used as input for the simulation are shown. The lifetime of the PV system is assumed to be 25 years. The discount rate is based on the rate of the central bank of Indonesia [31]. The system price of 4 \$/Wp is based on a PV module price of about 2 \$/Wp [32], which in Indonesia contributes for roughly 50% to the total system price including BOS, installation and power electronics [33].

[1] The annual capacity factor is defined as the annual kilowatt-hours generated for each kilowatt AC of peak capacity (kWh/kWp) divided by the number of hours in a year.

Table 5
Assumptions for LCOE calculation.

Variable	Value	Unit
Lifetime (L)	25	years
Annual operations (AO)	15	\$/kWp
Residual value (RV)	0.5	%
Discount rate (DR)	5.75	%
System degradation rate (SDR)	0.5	%
System price (P)	4	\$/Wp
Tax rate (TR)	25	%

Table 6
CO_2 grid emission factors (EF) (ton CO_2-eq/MWh$_e$) [36,37].

Grid name	EF (ton CO_2-eq/MWh$_e$)
Java–Madura–Bali (Jamali)[b]	0.73
Sumatra[b]	0.75
West Kalimantan[b]	0.73
South and Central Kalimantan[b]	0.96
East Kalimantan[b]	0.86
South Sulawesi, West Sulawesi[b]	0.61
N. Sulawesi, Gorontalo, C. Sulawesi[a]	0.16
Southeast Sulawesi[a]	0.27

[a] Data available by 2009.
[b] Respectively 2010.

3. Results

3.1. Electricity

The total potential of grid-connected PV in Indonesia, $E_{PV,pot}$, is 1492 TWh, which corresponds to about 10 times the total electricity demand of 2010. The share of this potential that is actually possible to develop taking the electricity demand into account, is 26%, 5% and 0.5% for urban cores, suburbs and villages, respectively.

Based on the described model, which limits the potential to the actual electricity demand, in total 37 TWh/year can be generated by grid-connected PV, which is about 26% of the total electricity consumption over 2010 according to the national electricity utility PLN [4]. Of the total electricity generated by grid-connected PV, 40% can be produced in the urban cores, 43% in the suburbs and 17% in villages.

The available area for solar PV is not a limiting factor in most provinces, only in the Jakarta region the calculated potential can be completely used, in other provinces this is not even close.

Based on an average capacity factor of 16%, the amount of 37 TWh/year could be supplied by about 27 GWp installed PV capacity, with a total required land area of about 190 km^2, assuming 15% module efficiency and a PR of 75%. The total potential, $E_{PV,pot}$, could be supplied by about 1100 GWp, requiring a land area of 7570 km^2 corresponding to 0.5% of the land area of Indonesia.

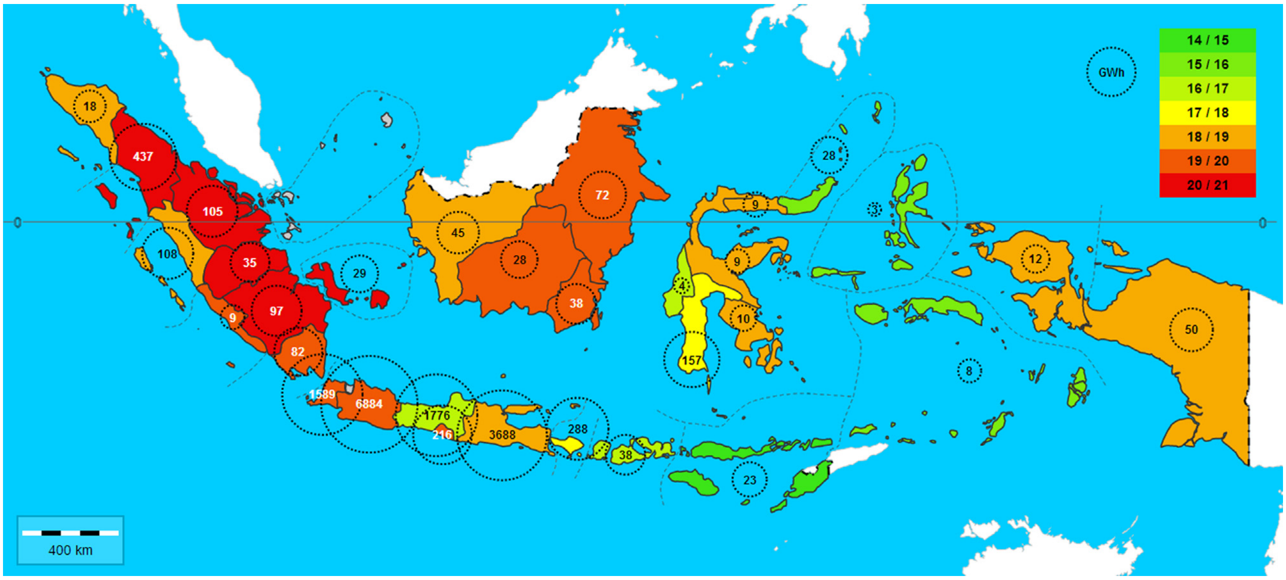

Fig. 7. Provinces of Indonesia, the colors show the difference in PLN's generation cost and the calculated LCOE for suburbs. Values in US$ cent/kWh. Provinces shown in gray do not have grid-connected suburban areas. The dotted circles indicate the potential amount of electricity generation by grid-connected PV in GWh/year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 7
Results sensitivity analysis of the average LCOE for urban cores in $/kWh.

Urban core	−50%	0%	50%	200%
Lifetime (*L*)	0.287	0.197	0.177	0.168
PV system price (*P*)	0.103	0.197	0.291	0.574
Discount rate (*DR*)	0.137	0.197	0.264	0.492
System degradation rate (*SDR*)	0.192	0.197	0.202	0.217
Annual operations (*AO*)	0.193	0.197	0.201	0.214
Residual value (*RV*)	0.205	0.197	0.189	0.167
Tax rate (*TR*)	0.214	0.197	0.180	0.130

Table 8
Results sensitivity analysis of the average LCOE for suburbs in $/kWh.

Suburb	−50%	0%	50%	200%
Lifetime (*L*)	0.268	0.184	0.165	0.156
PV system price (*P*)	0.096	0.184	0.272	0.536
Discount rate (*DR*)	0.128	0.184	0.246	0.460
System degradation rate (*SDR*)	0.179	0.184	0.189	0.203
Annual operations (*AO*)	0.180	0.184	0.188	0.200
Residual value (*RV*)	0.191	0.184	0.177	0.156
Tax rate (*TR*)	0.199	0.184	0.168	0.122

3.2. CO_2 reduction potential

PV has an average of 45 g CO_2-eq/kWh [34], while coal and oil have an average of 1000 and 800 g CO_2-eq/kWh, respectively [35]. In Table 6 the grid emission factors[2] of Indonesia are shown. For other regions without a large electricity grid, there is assumed that the power is generated based on oil with an emission factor of 0.8 ton CO_2-eq/MWh_e. As such 26 ton CO_2-eq/year could be reduced by PV systems.

[2] The grid emission factor is defined as the total annual CO_2 emissions from power plants connected to the grid divided by the total annual electricity produced by these power plants.

Table 9
Results sensitivity analysis of the average LCOE for villages in $/kWh.

Village	−50%	0%	50%	200%
Lifetime (*L*)	0.305	0.210	0.189	0.178
System price (P)	0.109	0.210	0.310	0.611
Discount rate (*DR*)	0.146	0.210	0.281	0.524
System degradation rate (*SDR*)	0.204	0.210	0.215	0.231
Annual operations (*AO*)	0.205	0.210	0.214	0.228
Residual value (*RV*)	0.218	0.210	0.202	0.177
Tax rate (*TR*)	0.227	0.210	0.192	0.139

3.3. LCOE

The LCOE of grid-connected PV has been calculated for each province. The LCOE for all provinces range from 0.15 to 0.22 $/kWh for urban areas and from 0.17 to 0.24 $/kWh for rural areas.

Compared with the subsidized residential electricity tariff of 0.08 $/kWh[3] (0.09 $/kWh for industry) [9,12], grid-connected PV ain't yet cost-effective in any province. However, the real generation cost of PLN is on average 0.12 $/kWh and ranging from 0.07 to 0.17 $/kWh [10]. Fig. 7 shows the calculated LCOE for suburban areas for each province. As can be seen, in the eastern provinces of Indonesia the LCOE of solar PV is a bit lower due to higher irradiation values in these provinces. Leading to a cost-effective potential of PV systems of 443 MWp which is 2% of total. We assume that in the nearby future cost-effectiveness will be possible for the major part of Indonesia due to a rapid reduction of costs of PV modules and BOS components as well as steadily increasing prices of fossil fuels in Indonesia.

3.4. Sensitivity analysis

To determine the variables that have a significant influence on the LCOE a sensitivity analysis is carried out. In Table 7 the results are shown, the values in $/kWh show the average LCOE in Indonesia for different input values.

[3] Depending on the actual exchange rate.

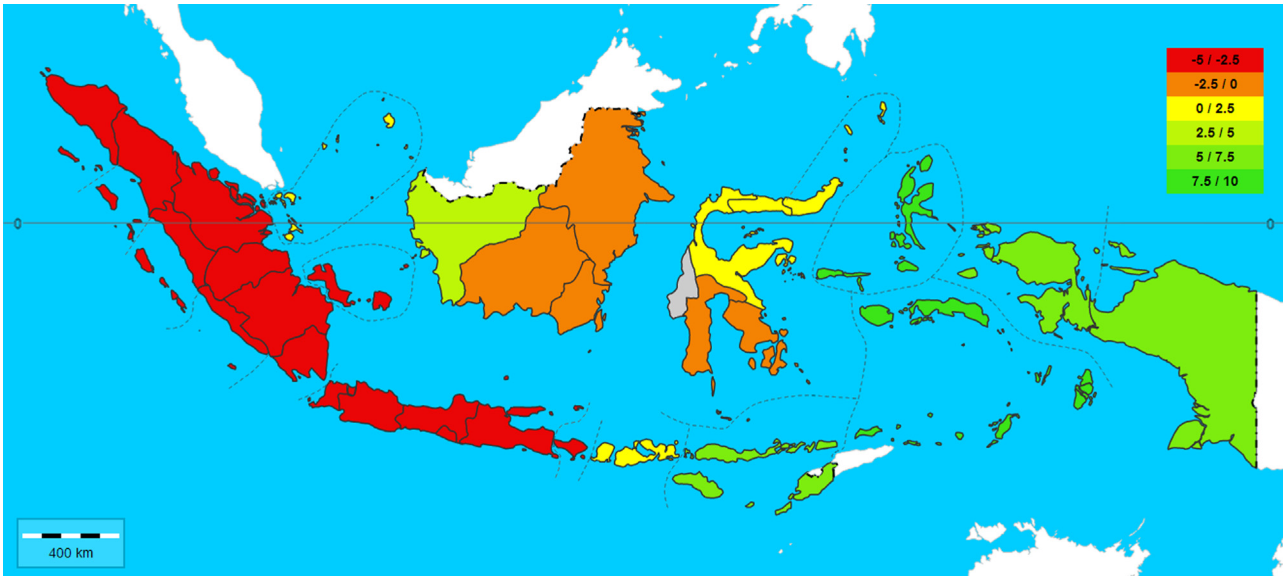

Fig. 8. The difference in LCOE of PV and PLN's generation cost for electricity per province for urban core areas in US dollar cents for a system price of 2 $/Wp. Positive values indicate that the LCOE is lower compared with the generation cost.

As can be seen, the implemented LCOE model is most sensitive to the system price and in a lesser extent to the discount rate. If the system price drops with 50%, the LCOE values of PV are competitive to PLN's electricity generation costs according to [10].

The differences among Tables 7–9 can be attributed to the various selected performance factors of the PV system for each area type.

Since the calculated potential of grid-connected PV is vast, the model is not very sensitive to changes in population densities of each classified area, which only affects the potential area and not the LCOE.

3.5. Tax incentives

The Indonesian government gives tax incentives to support investments in the renewable energy sector through regulation 21/2010 from Ministry of Finance Republic Indonesia [38]. The regulation provides for a reduction of net income up to 30% of the amount invested for 6 years (5% per year) and accelerated depreciation and amortization.

Taking this investment credit into account and applying the double declining balance method to calculate the annually depreciation, the LCOE of PV systems decreases with 0.015–0.024 $/kWh. The LCOE varies per province between 0.14–0.20 $/kWh, 0.13–0.19 $/kWh and 0.15–0.21 $/kWh, for urban cores, suburbs and villages, respectively.

3.6. Future outlook

It is expected that the PV system price will further decrease in the coming years because of higher module efficiencies and lower production costs due to economies of scale. In addition the Indonesian government is preparing a new pricing regulation for solar PV. The new price for electricity from solar power plants will be around IDR[4] 1880 ($0.20) to IDR 3135 ($0.33) per kWh, depending on the location [39]. With this feed-in tariff, investments in grid-connected PV systems will be profitable everywhere in Indonesia. Furthermore, PLN's electricity generation costs are expected to raise due to increasing fossil fuel prices, making PV more cost competitive.

To determine the future LCOE of PV for each province in Indonesia, the system price is assumed to reach $2/Wp around the year 2020 [40]. Other aspects that could influence the benchmarking of costs, such as for instance increasing oil prices or changes of discount rate, are not taken into account. In Figs. 8–10 the results are shown for the urban cores, suburbs and villages, respectively. The LCOE is subtracted from the PLN generation cost for each province in 2005 [10].

As can be seen from Figs. 8–10, the provinces wherein PV gets cheaper than PLN's generation costs are mainly the eastern provinces. However again we would like to repeat that with the new subsidy scheme, grid-connected PV will be both technically and economically feasible in all Indonesian provinces.

In Fig. 11 a similar map is shown for a system price of 1 $/Wp for suburban areas, with this system price grid-connected PV is cost-effective everywhere in Indonesia. Grid-parity for whole Indonesia is reached with a system price of 1.40 $/Wp, excluding increased fossil fuel prices.

4. Discussion and conclusions

The maximum amount of grid-connected PV in Indonesia of 37 TWh/year is limited by the current electricity demand. The total potential of grid-connected PV is found to be 1492 TWh. In the model presented this is related to the population size with grid connection, so this maximum potential increases with increasing electrification rates. The electricity demand grows about 9% per annual, which means that the amount of electricity that can be generated by PV will follow this trend.

The LCOE values for each province are determined for urban cores, suburban areas and rural villages. Since the LCOE is sensitive to the system price and the system price is assumed to be constant for each province, the actual LCOE can be influenced by transportation costs to more remote provinces. These costs are not taken into account yet, and according to the

[4] Indonesian rupiah, the exchange rate used for all calculations in this study is 1 USD=9624.00 IDR as of 2012-11-13 17:00 UTC, source: www.xe.com.

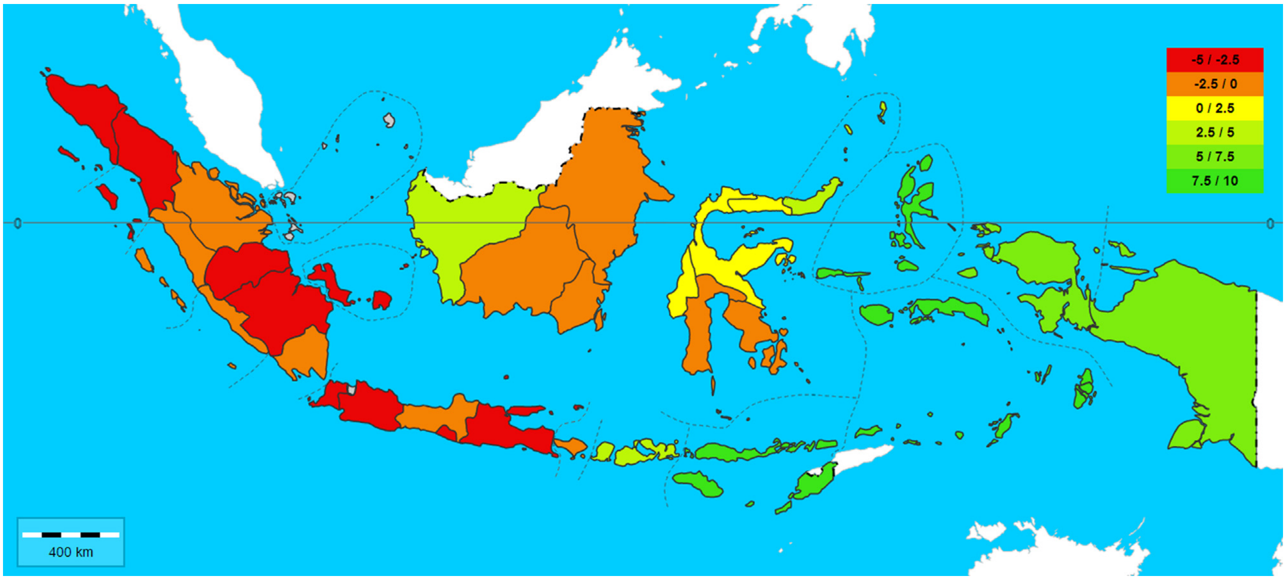

Fig. 9. The difference in LCOE of PV and PLN's generation cost for electricity per province for suburb areas in US dollar cents for a system price of 2 $/Wp. Positive values indicate that the LCOE is lower compared with the generation cost.

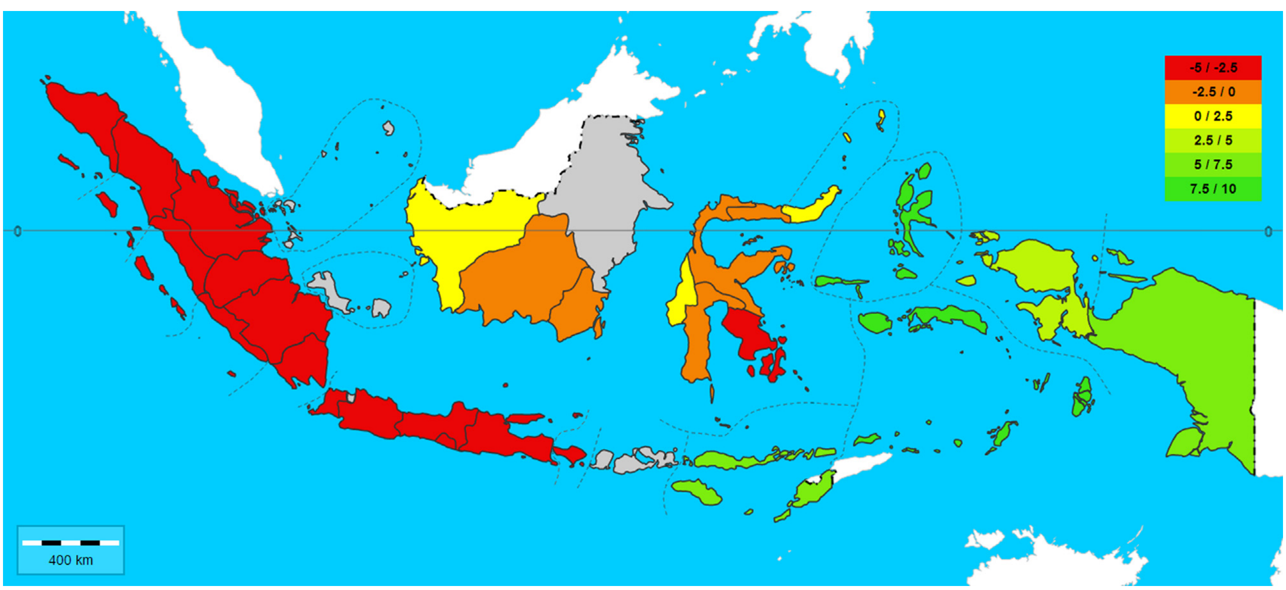

Fig. 10. The difference in LCOE of PV and PLN's generation cost for electricity per province for rural village areas in US dollar cents for a system price of 2 $/Wp. Positive values indicate that the LCOE is lower compared with the generation cost.

sensitivity analysis an increase of the system price by 50% leads to an increase of the LCOE by about 0.01 $/kWh. The remoteness of the location can influence the annual operation costs in a same way as well; however the LCOE is found to be less sensitive to these costs.

The method presented in this study to determine the area with an electricity grid assumes that there is no grid at all in rural areas, which is probably not the case in practice which will be a very dispersed electricity grid. Since the method is based on commonly available data (e.g. urbanization ratio, electrification ratio population), this method could be useful for other developing countries with a lack of grid distribution data as well.

The total potential of grid-connected PV in Indonesia, based on the current population size and land availability factors, is 1100 GWp, generating about 1492 TWh which is 10 times more than the electricity consumed in Indonesia in 2010.

Taking restrictions of the present electricity demand during day-time and a minimal base load of conventional power systems into account, the total potential is about 27 GWp, generating 37 TWh/year, which is about 26% of the total electricity consumption in Indonesia in 2010.

Compared with the energy potentials of other renewables in Indonesia, the present potential of grid-connected PV is similar to the potential of geothermal energy and roughly the half of the potential for biomass.

According to the calculated LCOE for each province at a system price of 4 $/Wp yet, PV cannot compete with the retail prices of electricity which are subsidized by the government. However, in some provinces, especially located in the part eastern of Indonesia, the LCOE of grid-connected PV in urban areas is at the edge of competition with the cost of the current electricity generation.

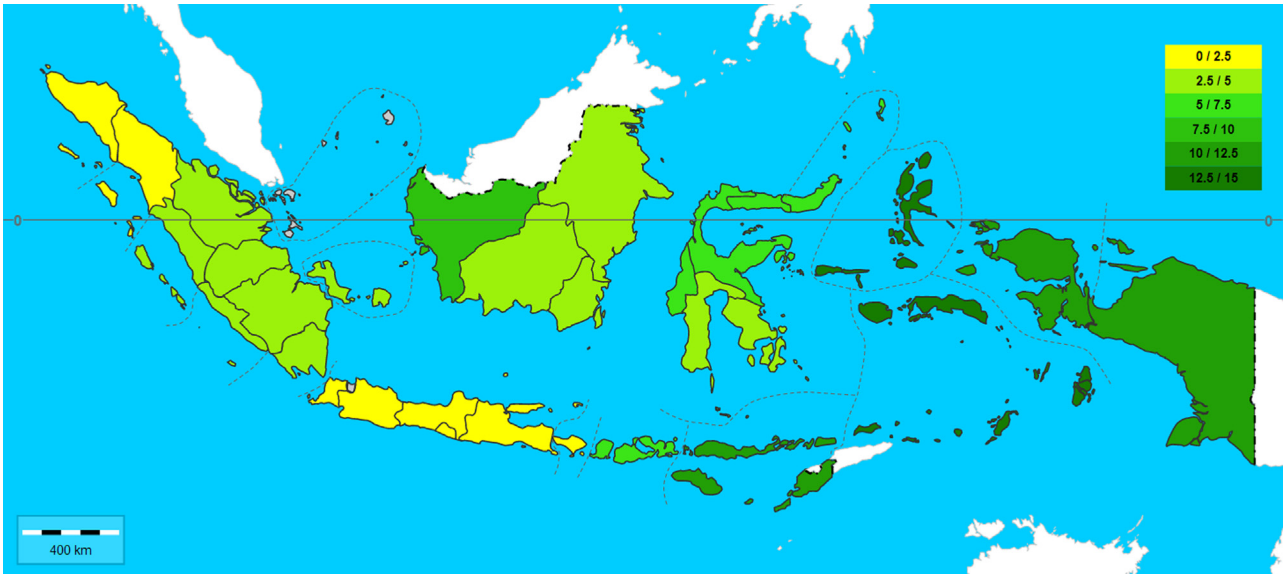

Fig. 11. The difference in LCOE of PV and PLN's generation cost for electricity per province for suburb areas in US dollar cents for a system price of 1 $/Wp.

According to the sensitivity analysis, the major factors of influence on the LCOE are the system price and the discount rate. It is shown that with a system price of 2 $/Wp PV systems are cost-effective for eastern Indonesia. At 1.40 $/Wp they are feasible for whole Indonesia, excluding increased fossil fuel prices. Anyhow with the upcoming feed-in tariff for PV energy and expected decline of PV system costs, grid-connected PV gets profitable in most parts of Indonesia.

From our study we conclude that grid-connected PV could play a key role in solving several energy related issues in Indonesia. It can help to increase electrification ratios on remote islands and to decrease the dependency on fossil fuels.

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